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Lakshmi Narayanan et al.

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(54) **SENSOR FUSION**

(71) Applicant: **Honda Motor Co., Ltd.**, Tokyo (JP)
(72) Inventors: **Athmanarayanan Lakshmi Narayanan**, Sunnyvale, CA (US);
Avinash Siravuru, Pittsburgh, PA (US)
(73) Assignee: **HONDA MOTOR CO., LTD.**, Tokyo (JP)

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CPC **G06N 3/082** (2013.01); **G06N 3/084** (2013.01)

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CPC G06N 3/082; G06N 3/084; G06N 3/08; G06N 3/0481; G06N 3/0445

See application file for complete search history.

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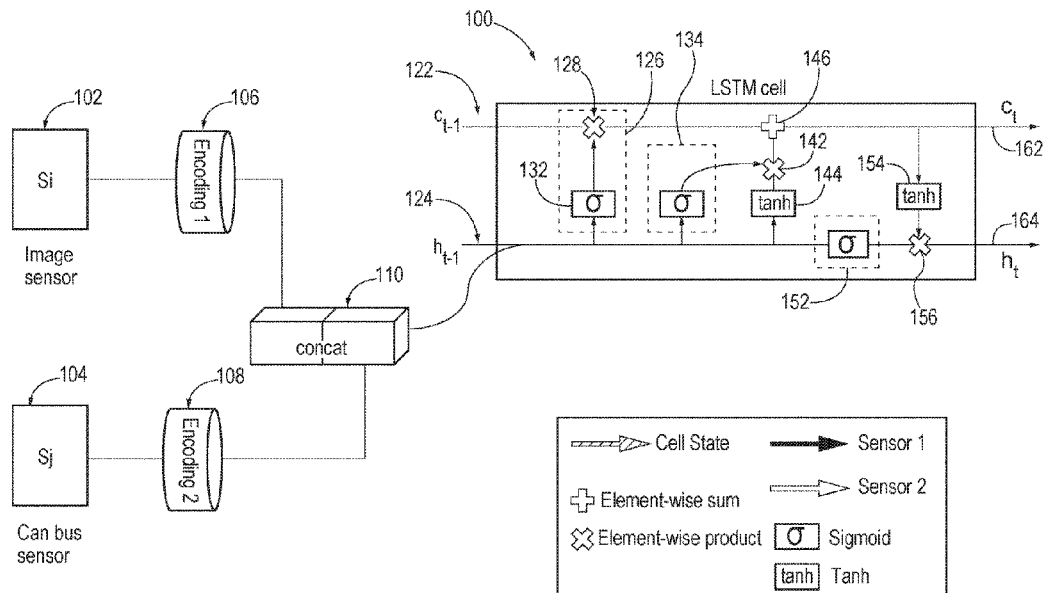
Primary Examiner — Jamal Javaid

(74) *Attorney, Agent, or Firm* — Rankin, Hill & Clark LLP

(57) **ABSTRACT**

According to one aspect, a method for sensor fusion associated with a long short-term memory (LSTM) cell may include generating a first adjusted sensor encoding based on a first sensor encoding from a first sensor, generating a second adjusted sensor encoding based on a second sensor encoding from a second sensor, generating a fusion result based on the first adjusted sensor encoding and the second adjusted sensor encoding, generating a first product based on the fusion result and the first adjusted sensor encoding, generating a second product based on the second adjusted sensor encoding, and generating a fused state based on the first product and the second product.

20 Claims, 12 Drawing Sheets



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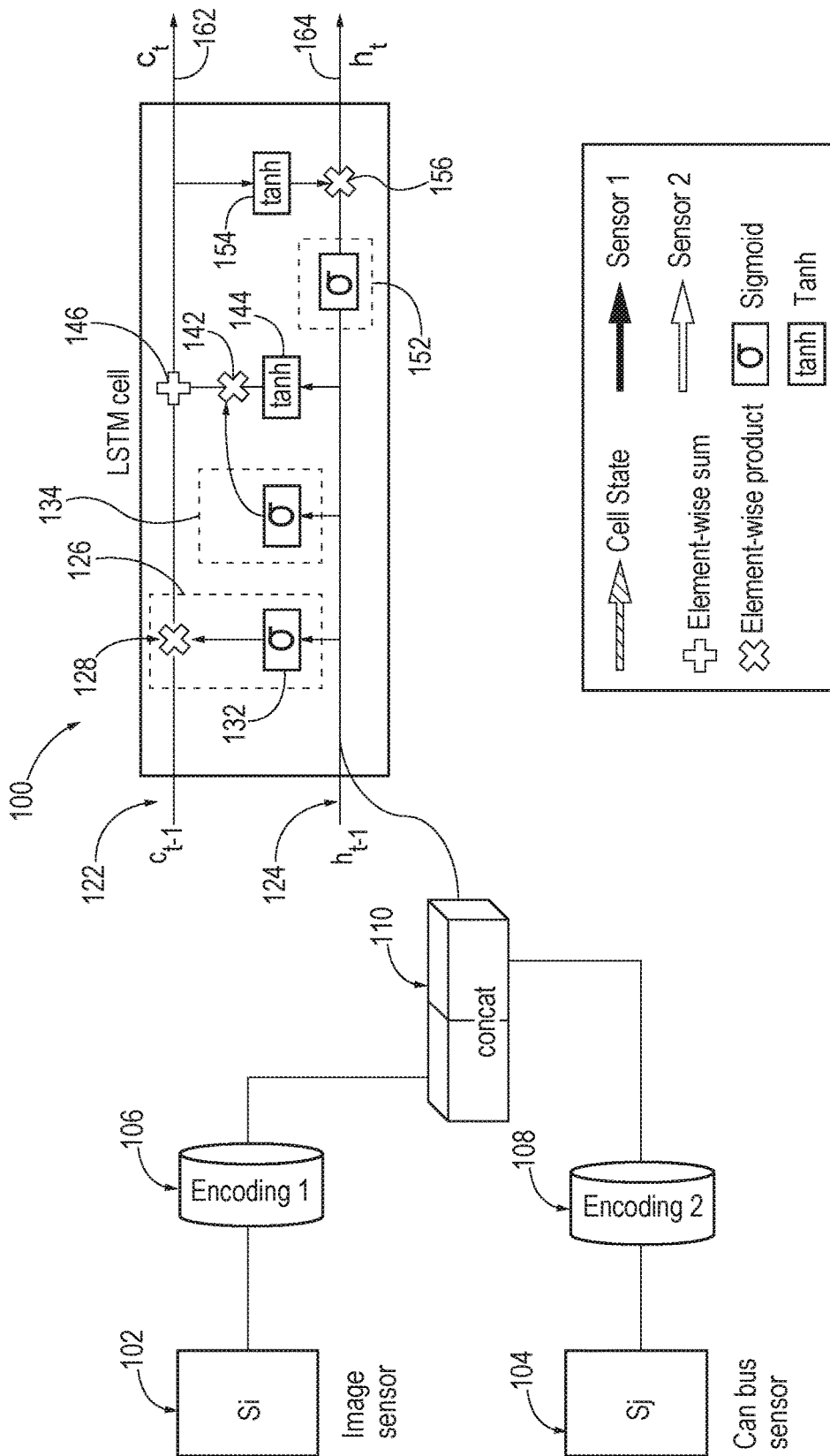


FIG. 1

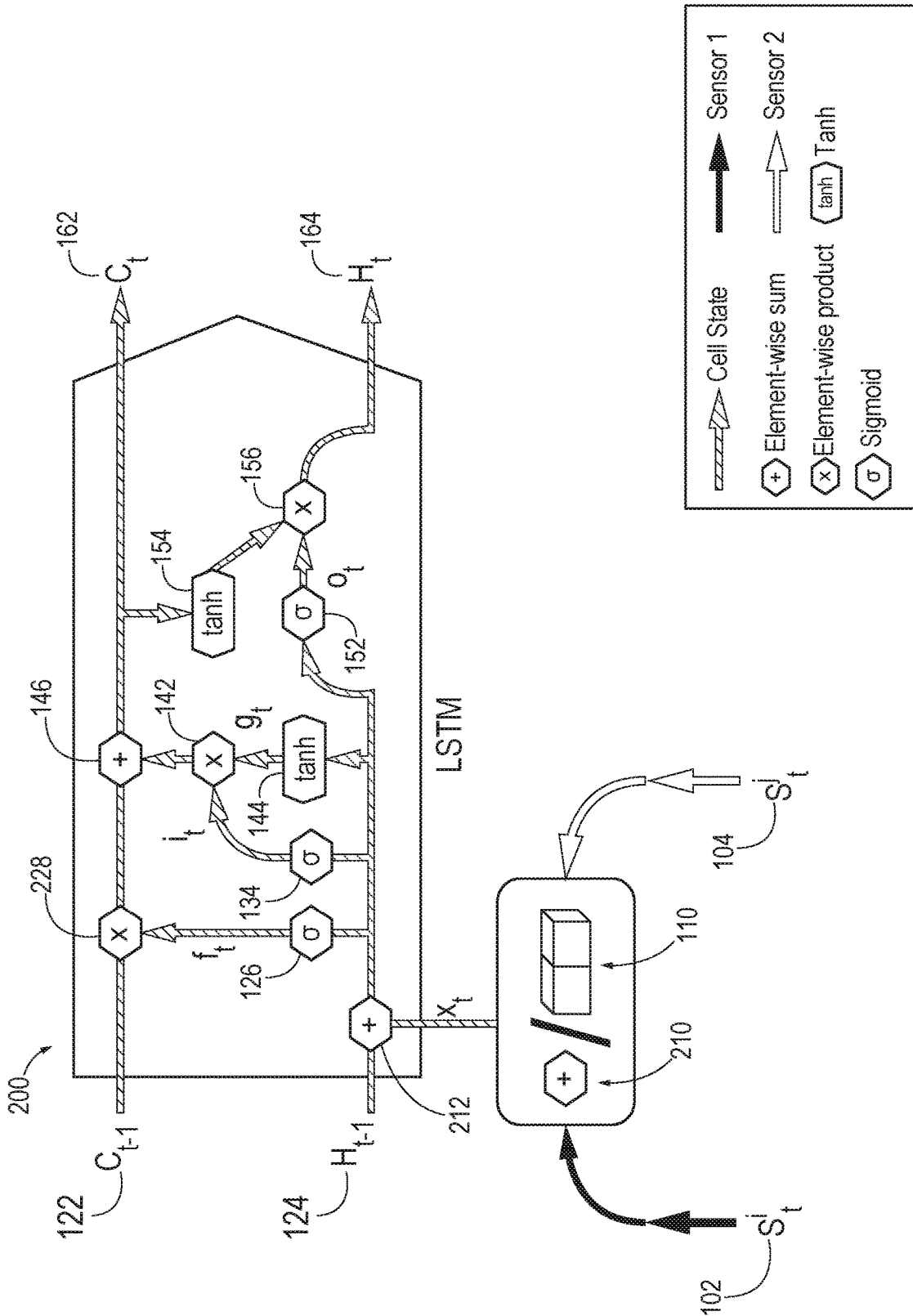
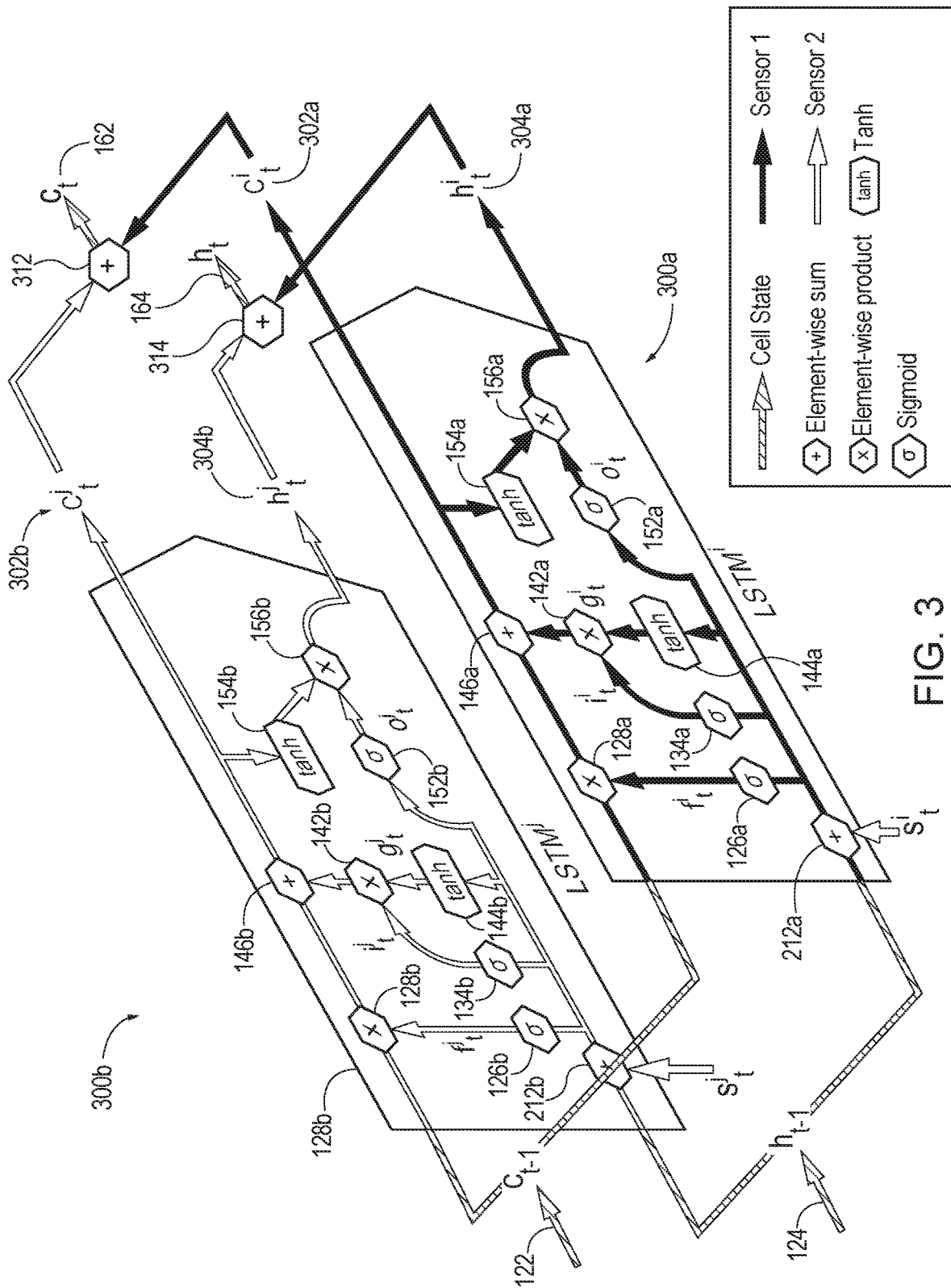


FIG. 2



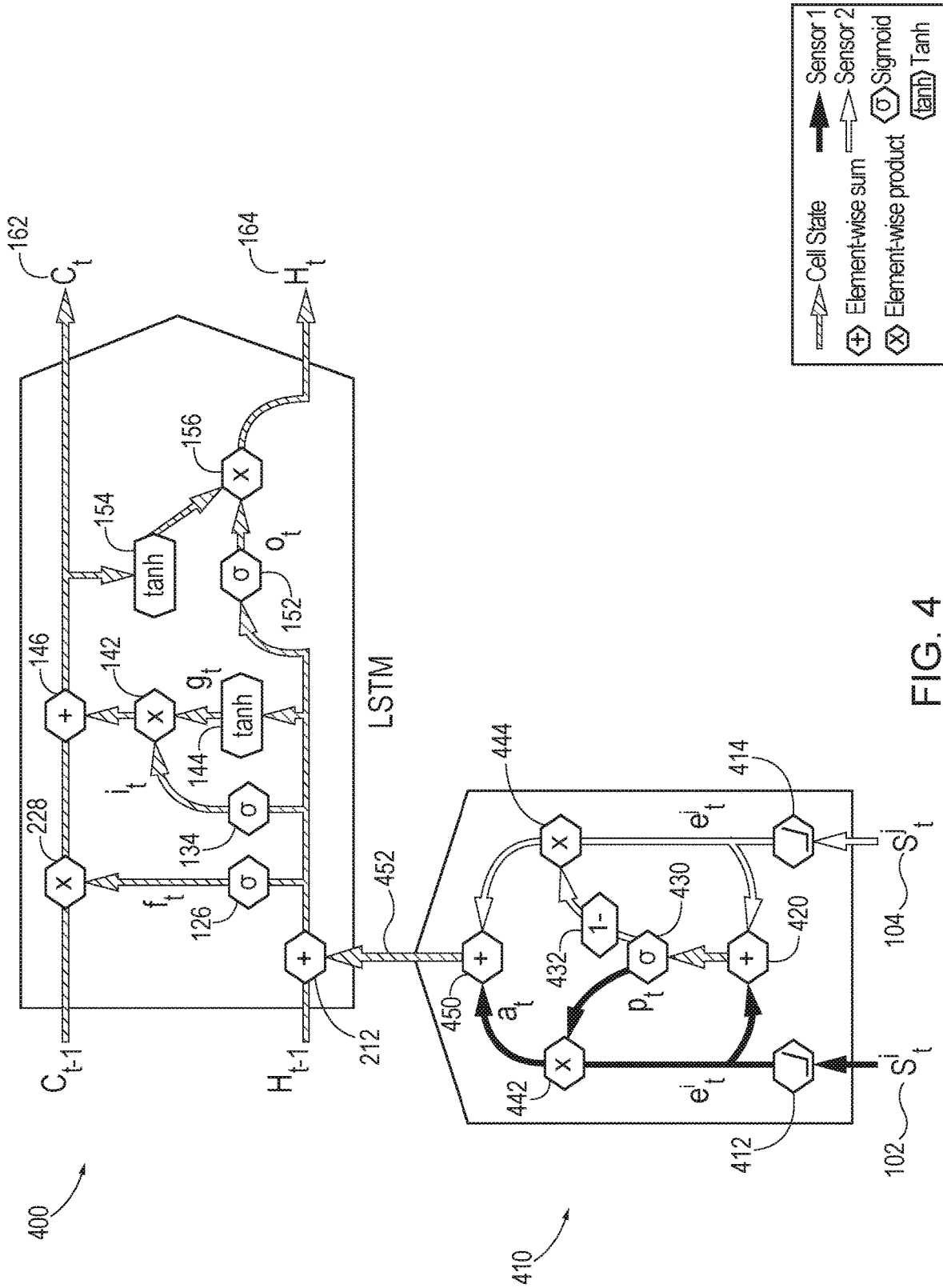
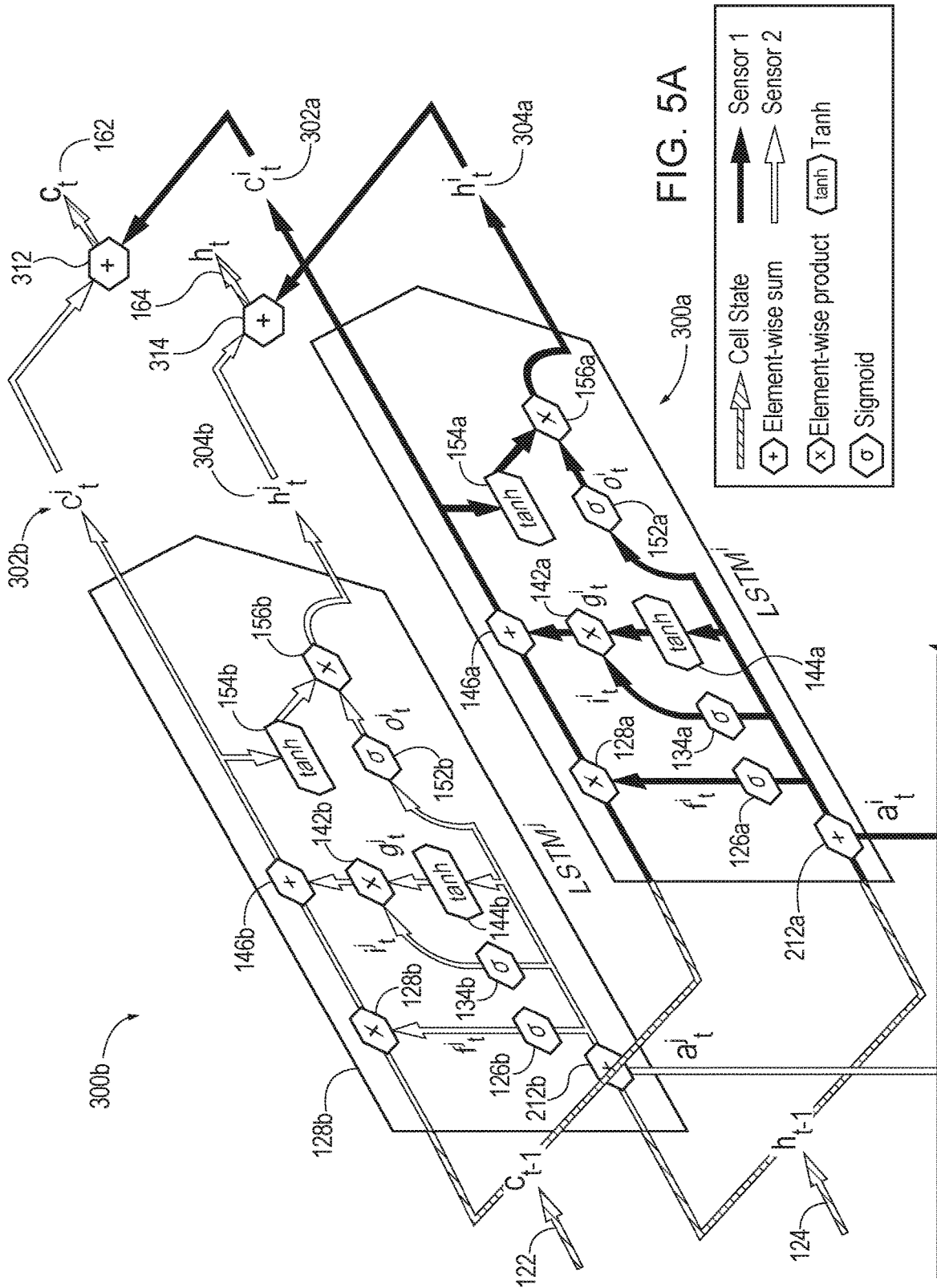


FIG. 4



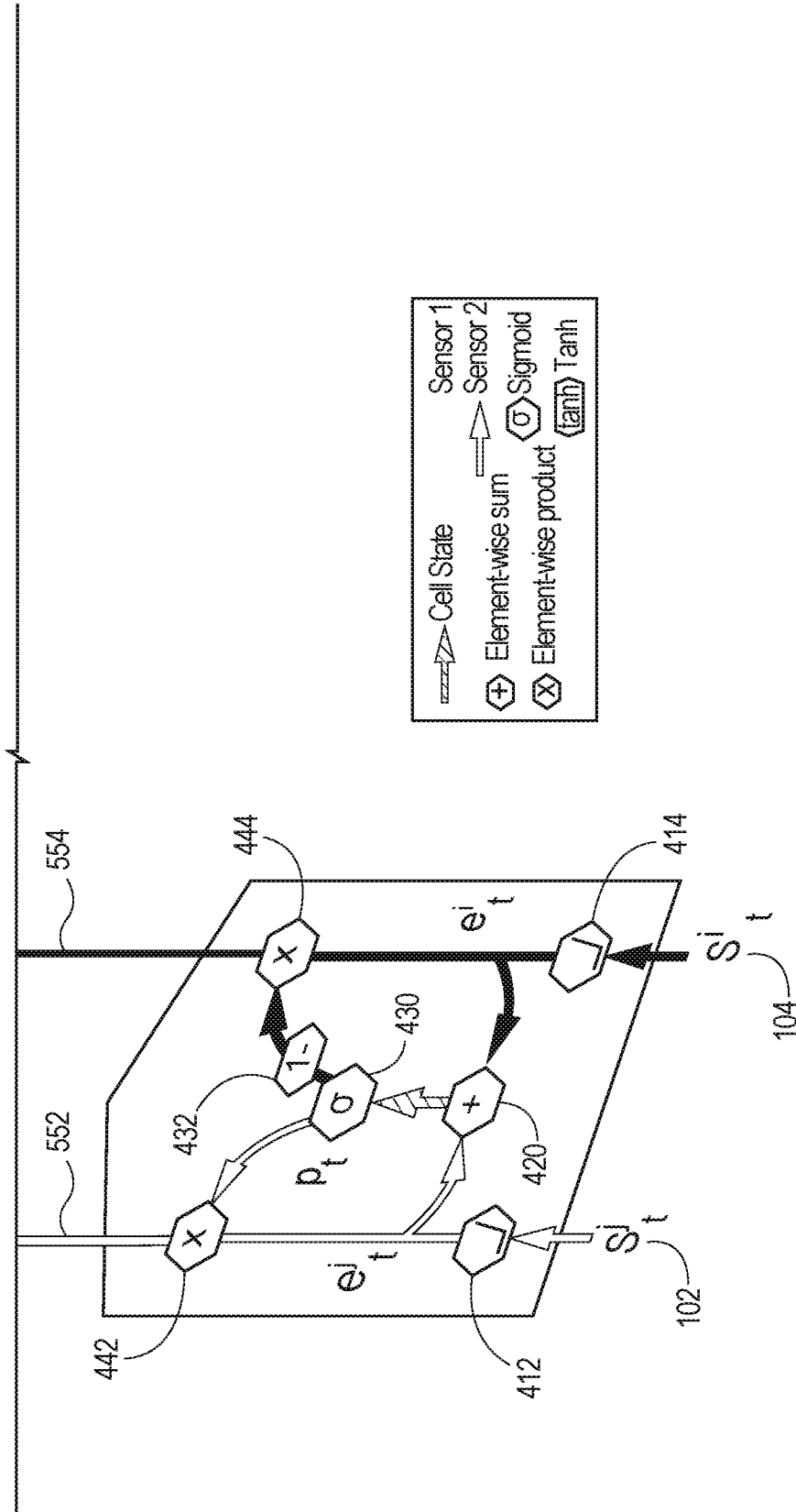


FIG. 5B

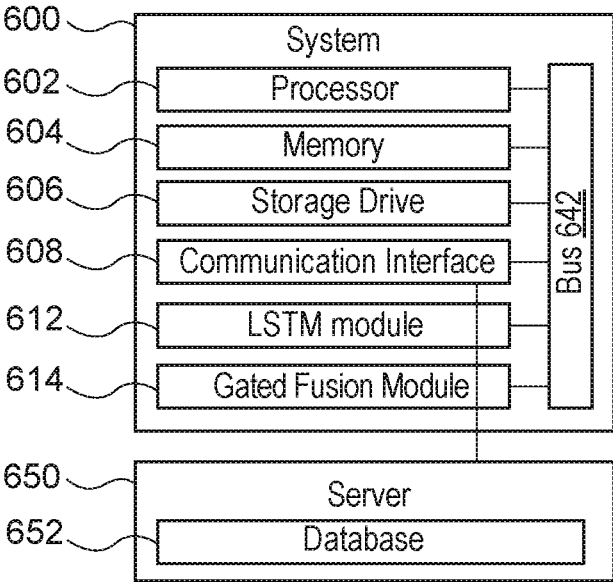


FIG. 6

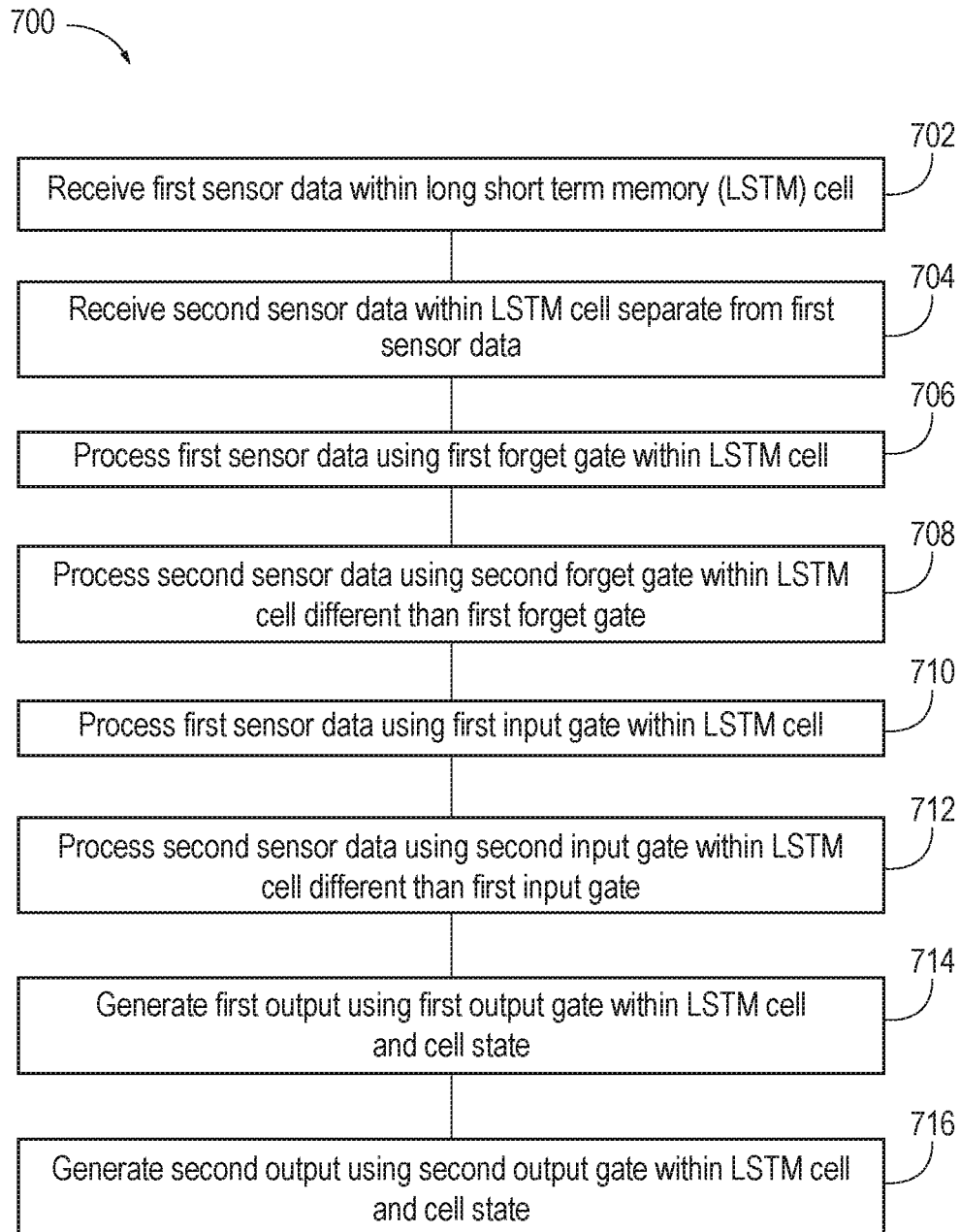


FIG. 7

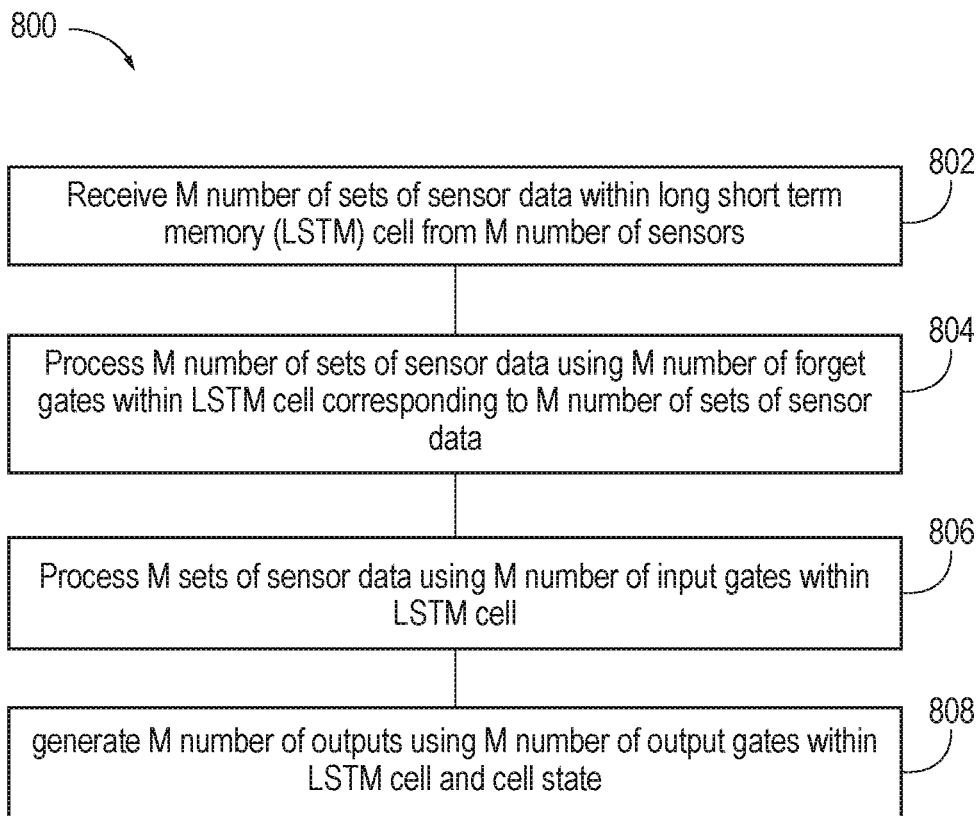


FIG. 8

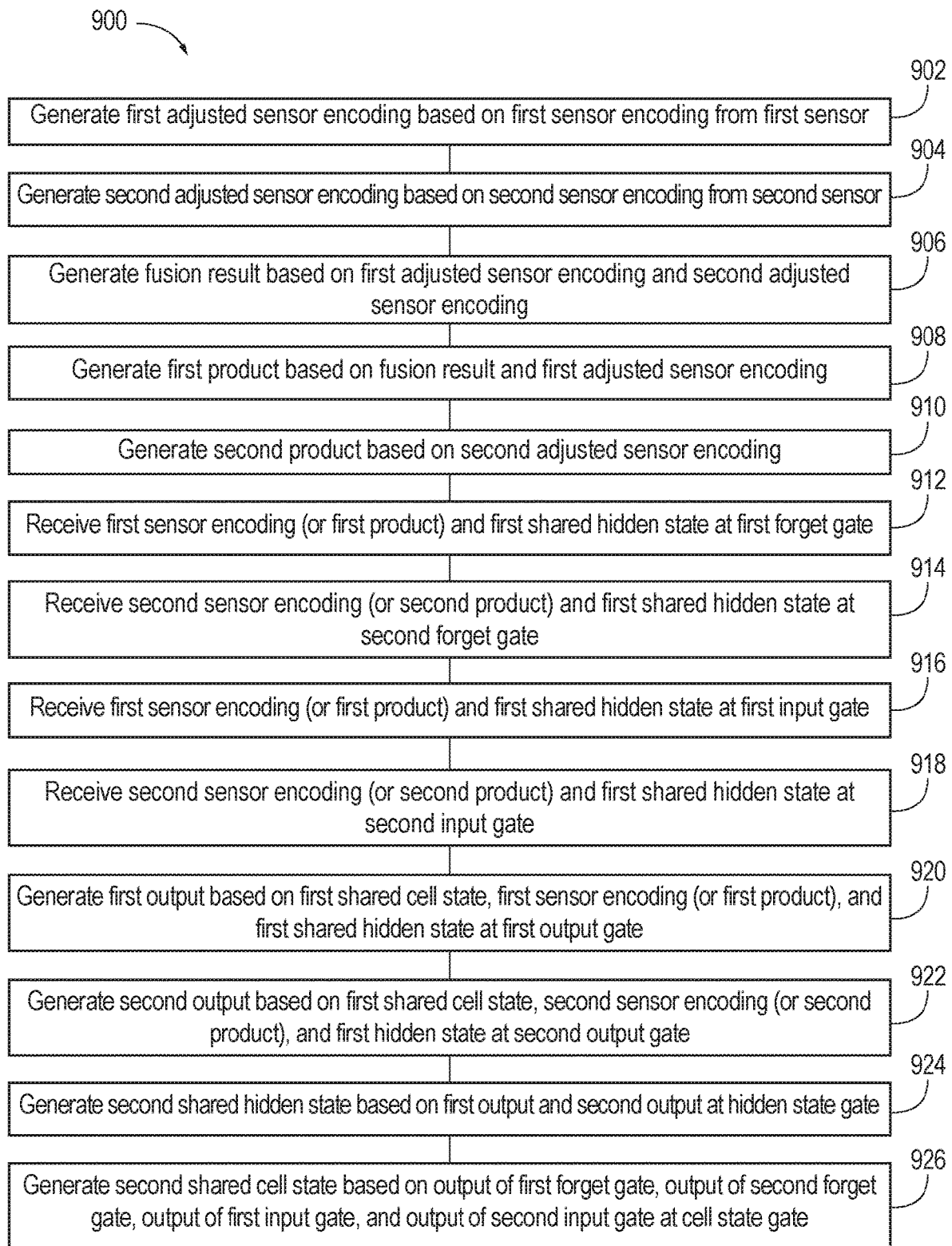


FIG. 9

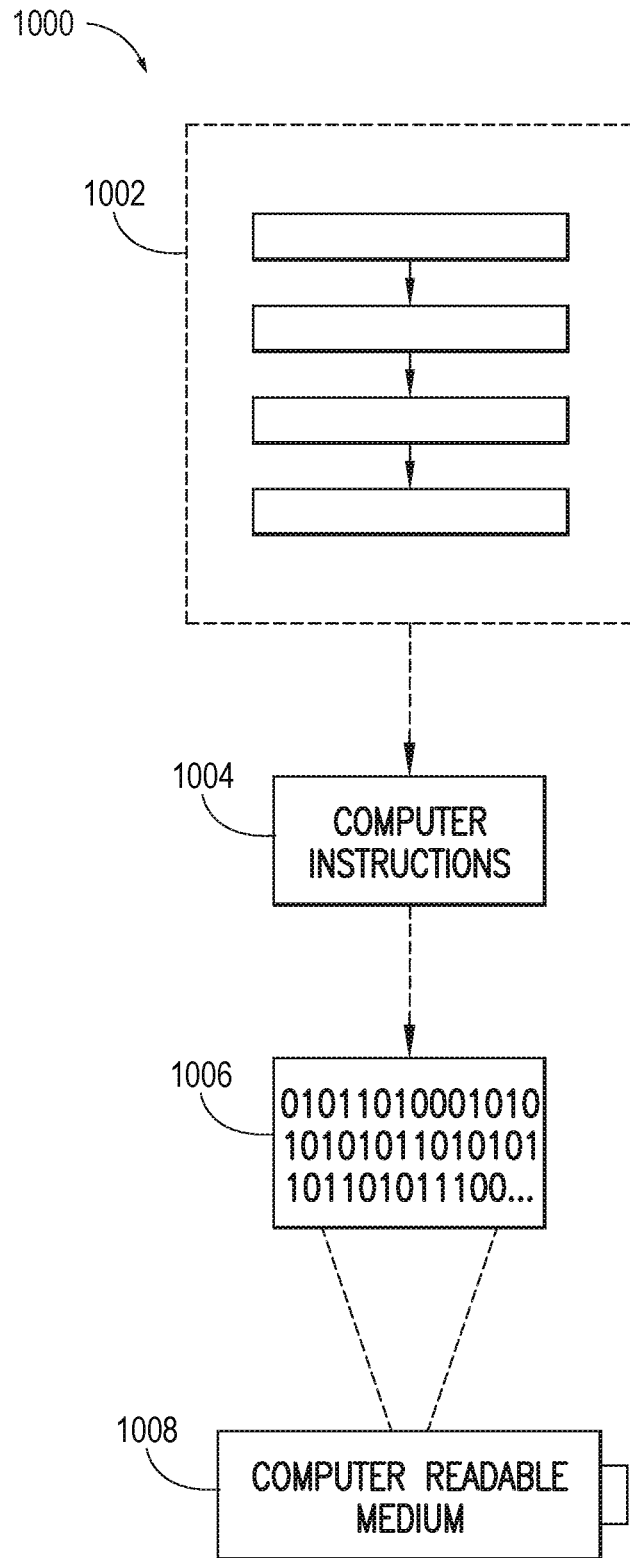


FIG. 10

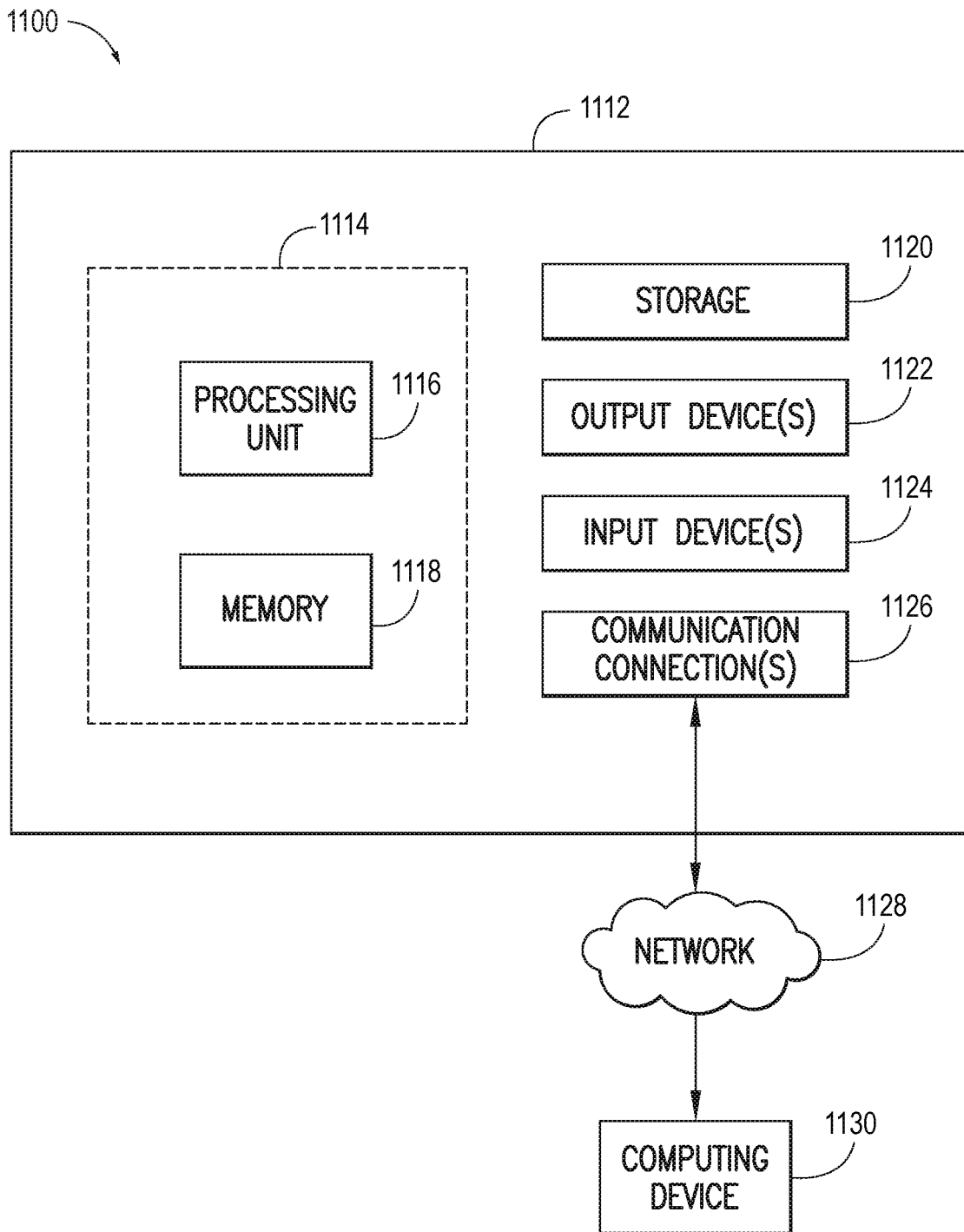


FIG. 11

1

SENSOR FUSION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part (CIP) of U.S. Non-Provisional patent application Ser. No. 16/664,356 entitled SENSOR FUSION, filed on Oct. 25, 2019, which claims the benefit of U.S. Provisional Patent Application, Ser. No. 62/870,460 entitled "SENSOR FUSION", filed on Jul. 3, 2019; the entirety of the above-noted applications is incorporated by reference herein.

BACKGROUND

A long short-term memory (LSTM) is an artificial recurrent neural network (RNN) architecture for deep learning or machine learning. An LSTM cell remembers values over arbitrary time intervals and regulates the flow of information into and out of the LSTM cell. During back propagation, recurrent neural networks may suffer from a vanishing gradient problem. Gradients are values used to update a neural networks weights. The vanishing gradient problem occurs when the gradient shrinks as it back propagates through time. If a gradient value becomes extremely small, the gradient may not contribute to the learning.

BRIEF DESCRIPTION

According to one aspect, a long short-term memory (LSTM) cell for sensor fusion may include a first forget gate, a second forget gate, a first input gate, a second input gate, a first output gate, a second output gate, a hidden state gate, and a cell state gate. The first forget gate may receive a first sensor encoding s_t^i and a first shared hidden state h_{t-1} . The second forget gate may receive a second sensor encoding s_t^j and the first shared hidden state h_{t-1} . The first input gate may receive the first sensor encoding s_t^i and the first shared hidden state h_{t-1} . The second input gate may receive second sensor encoding s_t^j and the first shared hidden state h_{t-1} . The first output gate may generate a first output based on a first shared cell state c_{t-1} , the first sensor encoding s_t^i , and the first shared hidden state h_{t-1} . The second output gate may generate a second output based on the first shared cell state c_{t-1} , the second sensor encoding s_t^j , and the first shared hidden state h_{t-1} . The hidden state gate may generate a second shared hidden state h_t based on the first output and the second output. The cell state gate may generate a second shared cell state c_t based on an output of the first forget gate, an output of the second forget gate, an output of the first input gate, and an output of the second input gate.

The first forget gate or the second forget gate may employ a sigmoid function to generate the output of the first forget gate or the output of the second forget gate, respectively. The output of the first forget gate $f_t^i = \sigma(W_f^i * s_t^i + U_f^i * h_{t-1} + b_f^i)$. The first input gate or the second input gate may employ a sigmoid function, a hyperbolic tangent function (tanh), or an element-wise product function to generate the output of the first input gate or the output of the second input gate, respectively. The output of the first input gate $i_t^i = \sigma(W_i^i * s_t^i + U_i^i * h_{t-1} + b_i^i)$. The first output gate or the second output gate may employ a sigmoid function, a hyperbolic tangent function (tanh), or an element-wise product function to generate an output of the first output gate or an output of the second output gate, respectively. The output of the first output gate $o_t^i = \sigma(W_o^i * s_t^i + h_{t-1} + b_o^i)$. The hidden state gate may generate

2

the second shared hidden state h_t by calculating an element-wise sum of the first output and the second output.

A first architecture within the LSTM cell may include the first forget gate, the first input gate, and the first output gate.

5 A second architecture within the LSTM cell may include the second forget gate, the second input gate, and the second output gate. The first architecture may be implemented in parallel to the second architecture. The first architecture may generate a first partial shared cell state $c_t^i = c_{t-1} \odot f_t^i + i_t^i \odot g_t^i$. The second architecture may generate a second partial shared cell state $c_t^j = c_{t-1} \odot f_t^j + i_t^j \odot g_t^j$. The cell state gate may generate the second shared cell state c_t by calculating an element-wise sum of the first partial shared cell state c_t^i and the second partial shared cell state c_t^j .

15 According to one aspect, a method for sensor fusion associated with a long short-term memory (LSTM) neural network may include receiving a first sensor encoding s_t^i and a first shared hidden state h_{t-1} at a first forget gate, receiving a second sensor encoding s_t^j and the first shared hidden state h_{t-1} at a second forget gate, receiving the first sensor encoding s_t^i and the first shared hidden state h_{t-1} at a first input gate, receiving second sensor encoding s_t^j and the first shared hidden state h_{t-1} at a second input gate, generating a first output based on a first shared cell state c_{t-1} , the first sensor encoding s_t^i , and the first shared hidden state h_{t-1} at a first output gate, generating a second output based on the first shared cell state c_{t-1} , the second sensor encoding s_t^j , and the first shared hidden state h_{t-1} at a second output gate, generating a second shared hidden state h_t based on the first output and the second output at a hidden state gate, and generating a second shared cell state c_t based on an output of the first forget gate, an output of the second forget gate, an output of the first input gate, and an output of the second input gate at a cell state gate.

35 The method for sensor fusion may include generating the output of the first forget gate or the output of the second forget gate by employing a sigmoid function. The method for sensor fusion may include generating the output of the first input gate or the output of the second input gate by employing a sigmoid function, a hyperbolic tangent function (tanh), or an element-wise product function. The method for sensor fusion may include generating an output of the first output gate or an output of the second output gate by employing a sigmoid function, a hyperbolic tangent function (tanh), or an element-wise product function.

45 According to one aspect, a long short-term memory (LSTM) cell for sensor fusion may include M number of forget gates, M number of input gates, and M number output gates. The M number of forget gates may receive M sets of sensor encoding data from M number of sensors and a shared hidden state h_{t-1} . The M number of input gates may receive the corresponding M sets of sensor data and the shared hidden state h_{t-1} . The M number output gates may generate M partial shared cell state outputs and M partial shared hidden state outputs based on the M sets of sensor encoding data, the shared hidden state h_{t-1} , and a shared cell state c_{t-1} . M may be ≥ 2 .

The LSTM cell for sensor fusion may include a cell state gate generating an updated shared cell state c_t by calculating an element-wise sum of the M partial shared cell state outputs. The LSTM cell for sensor fusion may include a hidden state gate generating an updated shared hidden state h_t by calculating an element-wise sum of the M partial shared hidden state outputs. The LSTM cell for sensor fusion may include a first architecture and a second architecture. The first architecture within the LSTM cell may include a first forget gate of the M number of forget gates,

a first input gate of the M number of input gates, and a first output gate of the M number of output gates. The second architecture within the LSTM cell may include a second forget gate of the M number of forget gates, a second input gate of the M number of input gates, and a second output gate of the M number of output gates. The first architecture may be implemented in parallel to the second architecture. The M number of forget gates, the M number of input gates, and the M number of output gates may employ a sigmoid function.

According to one aspect, a fusion cell associated with a long short-term memory (LSTM) cell may include a first rectifier, a second rectifier, a fusion gate, a first element-wise product gate, a second element-wise product gate, and an output gate. The first rectifier may receive a first sensor encoding s_t^i from a first sensor and generate a first adjusted sensor encoding e_t^i . The second rectifier may receive a second sensor encoding s_t^j from a second sensor and generate a second adjusted sensor encoding e_t^j . The fusion gate may receive the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j and generate a fusion gate result p_t^k . The first element-wise product gate may receive the fusion gate result p_t^k and the first adjusted sensor encoding e_t^i and generate a first product. The second element-wise product gate may receive $(1-p_t^k)$ and the second adjusted sensor encoding e_t^j and generate a second product. The output gate may receive the first product and the second product and generate a fused state a_t .

The first rectifier or the second rectifier may be a rectified linear unit (ReLU). The fusion gate may employ an element-wise sum function and a sigmoid function to generate the fusion gate result p_t^k based on the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j . The first element-wise product gate or the second element-wise product gate may employ an element-wise product function to generate the first product or the second product, respectively. The output gate may employ an element-wise sum function to generate the fused state a_t based on the first product and the second product. The first adjusted sensor encoding $e_t^i = \text{relu}(W_e^{i*} s_t^i)$. The fusion gate result $p_t^k = \sigma(\sum_{i=1}^M W_p^{i*} e_t^i)$, $\forall k \in [1, m-1]$.

The fused state $a_t = (\sum_{k=1}^{M-1} p_t^k \odot e_t^k) + (1 - \sum_{k=1}^{M-1} p_t^k) \odot e_t^M$. The fused state a_t may be input to a first gate of the LSTM cell which employs an element-wise sum function summing the fused state a_t and a hidden state h_{t-1} . An output of the first gate of the LSTM cell may be passed as an input to a forget gate of the LSTM cell.

According to one aspect, a fusion cell associated with a long short-term memory (LSTM) cell may include a first rectifier, a second rectifier, a fusion gate, a first element-wise product gate, and a second element-wise product gate. The first rectifier may receive a first sensor encoding s_t^i from a first sensor and generate a first adjusted sensor encoding e_t^i . The second rectifier may receive a second sensor encoding s_t^j from a second sensor and generate a second adjusted sensor encoding e_t^j . The fusion gate may receive the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j and generate a fusion gate result p_t^k . The first element-wise product gate may receive the fusion gate result p_t^k and the first adjusted sensor encoding e_t^i and generate a first product. The second element-wise product gate may receive $(1-p_t^k)$ and the second adjusted sensor encoding e_t^j and generate a second product.

The first adjusted sensor encoding $e_t^i = \text{relu}(W_e^{i*} s_t^i)$. The fusion gate result $p_t^k = \sigma(\sum_{i=1}^M W_p^{i*} e_t^i)$, $\forall k \in [1, M-1]$. The fusion gate may employ an element-wise sum function and a sigmoid function to generate the fusion gate result p_t^k

based on the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j . The first product may be input to a first gate of a first architecture within the LSTM cell which employs an element-wise sum function summing the first product and a hidden state h_{t-1} . The second product may be input to a first gate of a second architecture within the LSTM cell which employs an element-wise sum function summing the second product and a hidden state h_{t-1} .

According to one aspect, a method for sensor fusion associated with a long short-term memory (LSTM) cell may include generating a first adjusted sensor encoding e_t^i based on a first sensor encoding s_t^i from a first sensor, generating a second adjusted sensor encoding e_t^j based on a second sensor encoding s_t^j from a second sensor, generating a fusion result p_t^k based on the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j , generating a first product based on the fusion result p_t^k and the first adjusted sensor encoding e_t^i , generating a second product based on $(1-p_t^k)$ and the second adjusted sensor encoding e_t^j , and generating a fused state a_t based on the first product and the second product.

The first adjusted sensor encoding $e_t^i = \text{relu}(W_e^{i*} s_t^i)$. The fusion result $p_t^k = \sigma(\sum_{i=1}^M W_p^{i*} e_t^i)$, $\forall k \in [1, m-1]$. The fused state $a_t = (\sum_{k=1}^{M-1} p_t^k \odot e_t^k) + (1 - \sum_{k=1}^{M-1} p_t^k) \odot e_t^M$.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an illustration of an exemplary long short-term memory (LSTM) cell, according to one aspect.

FIG. 2 is an illustration of an exemplary long short-term memory (LSTM) cell, according to one aspect.

FIG. 3 is an illustration of an exemplary long short-term memory (LSTM) cell, according to one aspect.

FIG. 4 is an illustration of an exemplary long short-term memory (LSTM) cell and a fusion cell, according to one aspect.

FIGS. 5A-5B are illustrations of an exemplary long short-term memory (LSTM) cell and a fusion cell, according to one aspect.

FIG. 6 is an exemplary component diagram of a system for sensor fusion associated with the long short-term memory (LSTM) cells of FIGS. 1-5, according to one aspect.

FIG. 7 is an exemplary flow diagram of a method for sensor fusion associated with the long short-term memory (LSTM) cells of FIGS. 1-5, according to one aspect.

FIG. 8 is an exemplary flow diagram of a method for sensor fusion associated with the long short-term memory (LSTM) cells of FIGS. 1-5, according to one aspect.

FIG. 9 is an exemplary flow diagram of a method for sensor fusion associated with the long short-term memory (LSTM) cells of FIGS. 1-5, according to one aspect.

FIG. 10 is an illustration of an example computer-readable medium or computer-readable device including processor-executable instructions configured to embody one or more of the provisions set forth herein, according to one aspect.

FIG. 11 is an illustration of an example computing environment where one or more of the provisions set forth herein are implemented, according to one aspect.

DETAILED DESCRIPTION

The following includes definitions of selected terms employed herein. The definitions include various examples and/or forms of components that fall within the scope of a term and that may be used for implementation. The

examples are not intended to be limiting. Further, one having ordinary skill in the art will appreciate that the components discussed herein, may be combined, omitted or organized with other components or organized into different architectures.

A “processor”, as used herein, processes signals and performs general computing and arithmetic functions. Signals processed by the processor may include digital signals, data signals, computer instructions, processor instructions, messages, a bit, a bit stream, or other means that may be received, transmitted, and/or detected. Generally, the processor may be a variety of various processors including multiple single and multicore processors and co-processors and other multiple single and multicore processor and co-processor architectures. The processor may include various modules to execute various functions.

A “cell”, as used herein, may be implemented as a hardware circuit, integrated circuit (IC), etc. or implemented by the processor using digital signals, data signals, computer instructions, processor instructions, etc.

A “memory”, as used herein, may include volatile memory and/or non-volatile memory. Non-volatile memory may include, for example, ROM (read only memory), PROM (programmable read only memory), EPROM (erasable PROM), and EEPROM (electrically erasable PROM). Volatile memory may include, for example, RAM (random access memory), synchronous RAM (SRAM), dynamic RAM (DRAM), synchronous DRAM (SDRAM), double data rate SDRAM (DDRSDRAM), and direct RAM bus RAM (DRRAM). The memory may store an operating system that controls or allocates resources of a computing device.

A “disk” or “drive”, as used herein, may be a magnetic disk drive, a solid state disk drive, a floppy disk drive, a tape drive, a Zip drive, a flash memory card, and/or a memory stick. Furthermore, the disk may be a CD-ROM (compact disk ROM), a CD recordable drive (CD-R drive), a CD rewritable drive (CD-RW drive), and/or a digital video ROM drive (DVD-ROM). The disk may store an operating system that controls or allocates resources of a computing device.

A “bus”, as used herein, refers to an interconnected architecture that is operably connected to other computer components inside a computer or between computers. The bus may transfer data between the computer components. The bus may be a memory bus, a memory controller, a peripheral bus, an external bus, a crossbar switch, and/or a local bus, among others. The bus may also be a vehicle bus that interconnects components inside a vehicle using protocols such as Media Oriented Systems Transport (MOST), Controller Area network (CAN), Local Interconnect Network (LIN), among others.

A “database”, as used herein, may refer to a table, a set of tables, and a set of data stores (e.g., disks) and/or methods for accessing and/or manipulating those data stores.

An “operable connection”, or a connection by which entities are “operably connected”, is one in which signals, physical communications, and/or logical communications may be sent and/or received. An operable connection may include a wireless interface, a physical interface, a data interface, and/or an electrical interface.

A “computer communication”, as used herein, refers to a communication between two or more computing devices (e.g., computer, personal digital assistant, cellular telephone, network device) and may be, for example, a network transfer, a file transfer, an applet transfer, an email, a hypertext transfer protocol (HTTP) transfer, and so on. A computer communication may occur across, for example, a wireless

system (e.g., IEEE 802.11), an Ethernet system (e.g., IEEE 802.3), a token ring system (e.g., IEEE 802.5), a local area network (LAN), a wide area network (WAN), a point-to-point system, a circuit switching system, a packet switching system, among others.

A “mobile device”, as used herein, may be a computing device typically having a display screen with a user input (e.g., touch, keyboard) and a processor for computing. Mobile devices include handheld devices, portable electronic devices, smart phones, laptops, tablets, and e-readers.

A “vehicle”, as used herein, refers to any moving vehicle that is capable of carrying one or more human occupants and is powered by any form of energy. The term “vehicle” includes cars, trucks, vans, minivans, SUVs, motorcycles, scooters, boats, personal watercraft, and aircraft. In some scenarios, a motor vehicle includes one or more engines. Further, the term “vehicle” may refer to an electric vehicle (EV) that is powered entirely or partially by one or more electric motors powered by an electric battery. The EV may include battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). Additionally, the term “vehicle” may refer to an autonomous vehicle and/or self-driving vehicle powered by any form of energy. The autonomous vehicle may or may not carry one or more human occupants.

A “vehicle system”, as used herein, may be any automatic or manual systems that may be used to enhance the vehicle, driving, and/or safety. Exemplary vehicle systems include an autonomous driving system, an electronic stability control system, an anti-lock brake system, a brake assist system, an automatic brake prefill system, a low speed follow system, a cruise control system, a collision warning system, a collision mitigation braking system, an auto cruise control system, a lane departure warning system, a blind spot indicator system, a lane keep assist system, a navigation system, a transmission system, brake pedal systems, an electronic power steering system, visual devices (e.g., camera systems, proximity sensor systems), a climate control system, an electronic pretensioning system, a monitoring system, a passenger detection system, a vehicle suspension system, a vehicle seat configuration system, a vehicle cabin lighting system, an audio system, a sensory system, among others.

The aspects discussed herein may be described and implemented in the context of non-transitory computer-readable storage medium storing computer-executable instructions. Non-transitory computer-readable storage media include computer storage media and communication media. For example, flash memory drives, digital versatile discs (DVDs), compact discs (CDs), floppy disks, and tape cassettes. Non-transitory computer-readable storage media may include volatile and non-volatile, removable and non-removable media implemented in any method or technology for storage of information such as computer readable instructions, data structures, modules, or other data.

Early Recurrent Fusion (ERF)

FIG. 1 is an illustration of an exemplary long short-term memory (LSTM) cell 100, according to one aspect. The LSTM cell of FIG. 1 may include one or more gates and may receive input signals (e.g., a first sensor encoding s_t^i , a second sensor encoding s_t^j) from two or more sensors (e.g., S^i 102, S^j 104). According to one aspect, the two or more sensors S^i 102, S^j 104 may be of different sensor types (e.g., S^i 102 may be an image sensor, S^j 104 may be a controller area network bus sensor). Although FIG. 1 and some of the other figures described herein are described with reference to an image sensor and a CAN bus sensor, any other sensor types may be utilized. The two or more sensors S^i 102 (e.g.,

a first sensor), S^j **104** (e.g., a second sensor) may be of the same sensor type (i.e., both may be image sensors, etc.) or may be of different sensor types (e.g., image sensors, joint encoders, inertial measurement unit (IMU) data, graphics processing unit (GPU) data, audio sensors, touch sensors, tactile sensors, etc.).

A first encoding module **106** and a second encoding module **108**

may be configured to pre-process the sensor input signals or the first sensor encoding s_t^i and the second sensor encoding s_t^j and bring the respective encodings s_t^i , s_t^j to the same dimension prior to any sensor fusion. In this way, the first encoding module **106** and the second encoding module **108** process the first sensor encoding s_t^i and the second sensor encoding s_t^j , respectively, such that they are temporally correlated.

According to one aspect, Early Recurrent Fusion (ERF) may be implemented via concatenation or fusion via a concatenator **110**, which may concatenate, fuse, perform fusion, sum, etc. the respective encodings s_t^i , s_t^j . The output or result of the concatenator **110**, a first cell state c_{t-1} **122** (e.g., which may be a shared cell state across two or more architectures, which are discussed herein with respect to FIGS. **3** and **5A-5B**), and a first hidden state h_{t-1} **124** (e.g., which may be a shared hidden state across the two or more architectures, which are discussed herein with respect to FIGS. **3** and **5A-5B**) may be inputs to the LSTM cell **100** of FIG. **1**.

FIG. **1** is an illustration of an exemplary first architecture of the LSTM cell **100**, and according to one aspect, may be implemented in parallel with one or more additional architectures. The first architecture of the LSTM cell **100** of FIG. **1** may include a first forget gate **126** receiving the output or the result of the concatenator **110** (concatenation result of the first sensor encoding s_t^i **102** and the second sensor encoding s_t^j **104**) and the first hidden state h_{t-1} **124**. The first forget gate **126** may include or employ a sigmoid function **132** and an element-wise product function **128** to generate an output for the first forget gate **126**, which may be an intermediary result associated with a second cell state c_t **162**.

Additionally, the first architecture of the LSTM cell **100** of FIG. **1** may include a first input gate **134** receiving the output or the result of the concatenator **110** and the first hidden state h_{t-1} **124**. The first input gate **134** may include or employ a sigmoid function (e.g., **134**), an element-wise product function **142**, a hyperbolic tangent function (tanh) **144**, or an element-wise sum function **146** to generate an output of the first input gate **134**. The tanh function **144** may receive the output or the result of the concatenator **110** and the first hidden state h_{t-1} **124**, the element-wise product function **142** may be taken of an output of the tanh function **144** and an output of the sigmoid function **134**. An output of the element-wise product function **142** may be element-wise summed **146** with an output of the first forget gate **126** to thereby generate the second cell state c_t **162**.

The first architecture of the LSTM cell **100** of FIG. **1** may include an output gate **152**, which may include or employ a sigmoid function receiving the output or the result of the concatenator **110** and the first hidden state h_{t-1} **124**. The second cell state c_t **162** may be passed through a tanh function **154** resulting in an output for the tanh function **154**. An element-wise product **156** of the output for the tanh function **154** and the output gate **152** may be taken to generate a second hidden state h_t **164**.

FIG. **2** is an illustration of an exemplary LSTM cell, such as the LSTM cell **100** of FIG. **1**, described in greater detail, according to one aspect. In FIG. **2**, it may be seen that

concatenation may be performed by the concatenator **110** or an element-wise sum **210** of the first sensor encoding s_t^i **102** and the second sensor encoding s_t^j **104** may be calculated. The output of the concatenator **110** or the element-wise sum **210** may be designated as x_t , which may be element-wise summed **212** with the first hidden state h_{t-1} **124**. The output of the first forget gate **126**, which may include or employ the sigmoid function may be represented as f_t . The output of the sigmoid function associated with the input gate **134** may be represented as i_t . The output of the tanh function **144** associated with the input gate **134** may be represented as g_t . The output of the sigmoid function associated with the output gate **152** may be represented as o_t . According to one aspect, the element-wise product function **128** of the LSTM cell **100** of FIG. **1** may be implemented as an element-wise product function **228** of the first cell state c_{t-1} **122** and the output f_t of the first forget gate **126**. In this regard, the output of the element-wise product function **142** may be element-wise summed **146** with the output of the element-wise product function **228** to thereby generate the second cell state c_t **162**.

$$x_t = \dots + s_t^i + s_t^j \dots \text{ (or) } \dots s_t^i \oplus s_t^j \dots,$$

$$f_t = \sigma(W_f * x_t + U_f * h_{t-1} + b_f),$$

$$i_t = \sigma(W_i * x_t + U_i * h_{t-1} + b_i),$$

$$o_t = \sigma(W_o * x_t + U_o * h_{t-1} + b_o), \quad (1)$$

$$g_t = \tanh(W_g * x_t + U_g * h_{t-1} + b_g), \quad (2)$$

$$c_t = c_{t-1} \odot f_t + i_t \odot g_t,$$

$$h_t = o_t \odot \tanh(c_t) \quad (3)$$

Late Recurrent Summation (LRS)

FIG. **3** is an illustration of an exemplary LSTM cell including a first architecture **300a** and a second architecture **300b**, according to one aspect. While FIG. **3** is described with reference to merely the first architecture **300a** and the second architecture **300b**, additional architectures may be implemented in parallel in an array-like fashion for Late Recurrent Summation using M number of sensors.

The first architecture **300a** may include a first gate, which may include an element-wise sum function **212a** summing the first sensor encoding s_t^i **102** with a first shared hidden state h_{t-1} **124** and generating an output which may be passed to a first forget gate **126a**, a first input gate **134a**, a first tanh function **144a**, and a first output gate **152a** of the first architecture **300a**. The first forget gate **126a** may include or employ a sigmoid function and generate an output f_t^i . An element-wise product **128a** of the output f_t^i of the first forget gate **126a** and a first shared cell state c_{t-1} **122** may be calculated. The first shared hidden state h_{t-1} **124** and the first shared cell state c_{t-1} **122** may be shared or input into multiple architectures, such as the first architecture **300a**, the second architecture **300b**, a third architecture, etc. In this way, the first shared hidden state h_{t-1} **124** and the first shared cell state c_{t-1} **122** may be considered shared stated or common states.

The first input gate **134a** may include or employ a sigmoid function and generate an output i_t^i . The first tanh function **144a** may generate an output. The output i_t^i of the first input gate **134a** and the output of the first tanh function **144a** may be passed to an element-wise product function **142a**. The element-wise product function **142a** may generate an output by calculating the element-wise product of the output i_t^i of the first input gate **134a** and the output of the first tanh function **144a**. The output of the element-wise product

function **142a** may be element-wise summed **146a** with the output of the element-wise product function **128a**. An output of the element-wise sum function **146a** may be a first partial shared cell state c_t^i **302a**. The first partial shared cell state c_t^i **302a** may be passed to a first tanh function **154a**. The first output gate **152a** may include or employ a sigmoid function and generate an output. The output of the first output gate **152a** and an output of the first tanh function **154a** may be passed to an element-wise product function **156a**, which may generate a first partial shared hidden state h_t^i **304a**.

The second architecture **300b** may include a first gate, which may include an element-wise sum function **212b** summing the second sensor encoding s_t^j **104** with the same first shared hidden state h_{t-1} **124** (e.g., provided to the first architecture **300a**) and generating an output which may be passed to a second forget gate **126b**, a second input gate **134b**, a second tanh function **144b**, and a second output gate **152b** of the second architecture **300b**. The second forget gate **126b** may include or employ a sigmoid function and generate an output f_t^j . An element-wise product **128b** of the output f_t^j of the second forget gate **126b** and the same first shared cell state c_{t-1} **122** (e.g., provided to the first architecture **300a**) may be calculated.

The second input gate **134b** may include or employ a sigmoid function and generate an output i_t^j . The second tanh function **144b** may generate an output. The output i_t^j of the second input gate **134b** and the output of the second tanh function **144b** may be passed to an element-wise product function **142b**. The element-wise product function **142b** may generate an output by calculating the element-wise product of the output i_t^j of the second input gate **134b** and the output of the second tanh function **144b**. The output of the element-wise product function **142b** may be element-wise summed **146b** with the output of the element-wise product function **128b**. An output of the element-wise sum function **146b** may be a second partial shared cell state c_t^j **302b**. The second partial shared cell state c_t^j **302b** may be passed to a second tanh function **154b**. The second output gate **152b** may include or employ a sigmoid function and generate an output. The output of the second output gate **152b** and an output of the second tanh function **154b** may be passed to an element-wise product function **156b**, which may generate a second partial shared hidden state h_t^j **304b**.

The second architecture **300b** may be identical to the first architecture **300a**, except that the second architecture **300b** may receive the second sensor encoding s_t^j **104** as an input rather than the first sensor encoding s_t^i **102**. Element-wise sum functions for a cell state gate **312** and a hidden state gate **314** may sum the first partial shared cell state c_t^i **304a** with the second partial shared cell state c_t^j **304b** and the first partial shared hidden state h_t^i **302a** with the second partial shared hidden state h_t^j **302b**, to generate a second shared cell state c_t **162** and a second shared hidden state h_t **164**, respectively. Should additional architectures be implemented, the element-wise sum functions for the cell state gate **312** and the hidden state gate **314** may sum additional partial shared cell states and/or additional partial shared hidden states accordingly (e.g., $c_t^i+c_t^j+c_t^k$ or $h_t^i+h_t^j+h_t^k$).

According to one aspect of Late Recurrent Summation, there may be M copies of the LSTM units or architectures (e.g., **300a**, **300b**, etc. or one for each sensor). For each modality, a separate forget, input, output and cell state may be calculated. Weights, W^* , U^* , and biases, b^* , that transform the input space for each gate are unique for each modality but may be shared across time. Thus, each LSTM unit or architecture may receive information from the states of the past time step via the shared states (e.g., the first

shared hidden state h_{t-1} **124** and the first shared cell state c_{t-1} **122**) and the input from the current time step, s_t (e.g., corresponding sensor input).

Now, instead of having separate states of each LSTM unit of a sensor, all the architectures receive the same shared states or common states (e.g., the first shared hidden state h_{t-1} **124** and the first shared cell state c_{t-1} **122**) obtained from the previous time-step. In this way, fused representations may be propagated temporally. By sharing the past shared cell state c_{t-1} across all sensors, the model may individually decide whether to retain or discard memory for each modality. As discussed above, the partial shared hidden and cell states are added to produce a combined representation for the second shared cell state c_t and the second shared hidden state h_t that may be sent or passed to the next time step.

$$\begin{aligned} f_t^i &= \sigma(W_f^i * s_t^i + U_f^i * h_{t-1} + b_f^i), \\ i_t^i &= \sigma(W_i^i * s_t^i + U_i^i * h_{t-1} + b_i^i), \\ \alpha_t^i &= \sigma(W_o^i * s_t^i + U_o^i * h_{t-1} + b_o^i), \\ g_t^i &= \tanh(W_g^i * s_t^i + U_g^i * h_{t-1} + b_g^i), \end{aligned} \quad (4)$$

$$\begin{aligned} c_t^i &= c_{t-1} \odot f_t^i + i_t^i \odot g_t^i, \\ h_t^i &= \alpha_t^i \odot \tanh(c_t^i), \end{aligned} \quad (5)$$

$$c_t = \sum_{i=1}^M c_t^i, h_t = \sum_{i=1}^M h_t^i \quad (6)$$

In this regard, the architecture disclosed in FIG. 3 (e.g., including the first architecture **300a** and the second architecture **300b**) may classify what a driver is doing based on sensor encodings, such as the first sensor encoding s_t^i **102** and the second sensor encoding s_t^j **104**, from two or more sensors (e.g., a video or image capture sensor and CAN bus) and predict what an output, such as vehicle steering should be to approach a driving scenario, based on the respective encodings s_t^i , s_t^j . Examples of different types of sensor encodings may include image capture, video, LiDAR, CAN bus, tactile sensors, etc. Further, each one of the first architecture **300a**, the second architecture **300b**, a third architecture (no shown), a fourth architecture, etc., may include its own forget gate, input gate, output gate, etc. and may be configured to compute its own candidate or partially computed cell state (e.g., first partial shared cell state c_t^i **302a**, second partial shared cell state c_t^j **302b**, third partial shared cell state c_t^k (not shown in FIG. 3), etc.), while sharing the common hidden state (e.g., first hidden state h_{t-1} **124**, second hidden state h_t **164**, for the following stage) and the common cell state (e.g., first shared cell state c_{t-1} **122**, second shared cell state c_t **162** for the following stage), and is repeated over time t.

FIG. 4 is an illustration of an exemplary LSTM cell **400** and a fusion cell **410**, according to one aspect. The LSTM cell **400** may be identical to the LSTM cell **200** of FIG. 2 with the exception of the concatenator **110** and/or the element-wise sum **210** of the first sensor encoding s_t^i **102** and the second sensor encoding s_t^j **104**. Instead, an output of the fusion cell **410** may be input to the element-wise sum function **212**, as will be discussed herein.

The output of the fusion cell **410** may be element-wise summed **212** with the first hidden state h_{t-1} **124**. The output of the first forget gate **126**, which may include or employ the sigmoid function may be represented as f_t . The output of the sigmoid function associated with the input gate **134** may be represented as i_t . The output of the tanh function **144** associated with the input gate **134** may be represented as g_t . The output of the sigmoid function associated with the

output gate 152 may be represented as o_r . The LSTM cell 400 may include the element-wise product function 228 of the first cell state c_{r-1} 122 and the output f_r of the first forget gate 126. The output of the element-wise product function 142 may be element-wise summed 146 with the output of the element-wise product function 228 to generate the second cell state c_r 162.

The fusion cell 410 may include a first rectifier 412, a second rectifier 414, a fusion gate 420, a sigmoid function gate 430, a function gate 432, a first element-wise product gate 442, a second element-wise product gate 444, and an output gate 450. The first rectifier 412 or the second rectifier 414 may be a rectified linear unit (ReLU).

The first rectifier 412 may receive the first sensor encoding s_r^i from the first sensor and may generate a first adjusted sensor encoding e_r^i . The first adjusted sensor encoding may be calculated as $e_r^i = \text{relu}(W_e^{i*} s_r^i)$. The second rectifier 414 may receive the second sensor encoding s_r^j from the second sensor and may generate a second adjusted sensor encoding e_r^j . The first adjusted sensor encoding e_r^i may be passed to the fusion gate 420 and the first element-wise product gate 442. The second adjusted sensor encoding e_r^j may be passed to the fusion gate 420

and the second element-wise product gate 444. The fusion gate 420

may receive the first adjusted sensor encoding e_r^i and the second adjusted sensor encoding e_r^j and generate a fusion gate result p_r^k , which may be passed to the sigmoid function gate 430. The fusion gate result may be calculated as $p_r^k = \sigma(\sum_{i=1}^M W_p^{i*} e_r^i)$, $\forall k \in [1, m-1]$. The output of the sigmoid function gate 430

may be passed to the first element-wise product gate 442 and the function gate 432. The function gate 432 may calculate a $(1-p_r^k)$ value. The first element-wise product gate 442 may receive the fusion gate result p_r^k and the first adjusted sensor encoding e_r^i and generate a first product, which may be passed to the output gate 450 to be element-wise summed. The second element-wise product gate 444 may receive the $(1-p_r^k)$ from the function gate 432 and the second adjusted sensor encoding e_r^j and generate a second product, which may be passed to the output gate 450 to be element-wise summed with the first product. The first element-wise product gate 442 or the second element-wise product gate 444 may employ an element-wise product function to generate the first product and/or the second product. The fusion gate 450 may employ an element-wise sum function and a sigmoid function to generate the fusion gate result p_r^k based on the first adjusted sensor encoding e_r^i and the second adjusted sensor encoding e_r^j .

In this regard, the output gate 450 may receive the first product and the second product and generate a fused state a_r 452, which may be passed as the input to the element-wise sum function 212 of the LSTM cell 400. In this way, the fusion cell 410 may be utilized to generate inputs for LSTM cells by preprocessing the sensor encodings. As previously discussed, the fused state a_r 452 may be element-wise summed 212 with the first hidden state h_{r-1} 124. The output gate 450 may employ an element-wise sum function to generate the fused state a_r 452 based on the first product and the second product. The fused state a_r 452 may be calculated as $a_r = (\sum_{k=1}^{M-1} p_r^k \odot) + (1 - \sum_{k=1}^{M-1} p_r^k) [e_r^k]$. The fused state a_r 452 may be input to a first gate (e.g., element-wise sum 212) of the LSTM cell employing an element-wise sum function summing the fused state a_r 452 and the hidden state h_{r-1} . In this way, an output of the first gate or element-wise sum 212 of the LSTM cell 400 may be fed as an input to a forget gate of the LSTM cell 400.

FIGS. 5A-5B are illustrations of an exemplary LSTM cell and a fusion cell, according to one aspect. The architecture of FIGS. 5A-5B may be identical or similar to a combination of the LSTM cell including the first architecture 300a and the second architecture 300b of FIG. 3 and the fusion cell 410, which may be modified slightly. As previously discussed, while FIGS. 5A-5B are described with reference to merely the first architecture 300a and the second architecture 300b, additional architectures may be implemented in parallel in an array-like fashion for Late Recurrent Summation using M number of sensors, each having an architecture, structure, and/or configuration identical to the first architecture 300a, the second architecture 300b, etc.

For example, with reference to FIG. 5A, the first architecture 300a may include the element-wise sum function 212a summing the product or output associated with the second element-wise product gate 444 with the first shared hidden state h_{r-1} 124. The element-wise sum function 212a may generate an output which may be passed to the first forget gate 126a, the first input gate 134a, the first tanh function 144a, and the first output gate 152a of the first architecture 300a. The first forget gate 126a may include or employ the sigmoid function and generate an output f_r^i . The element-wise product 128a of the output f_r^i of the first forget gate 126a and the first shared cell state c_{r-1} 122 may be calculated.

The first input gate 134a may include or employ the sigmoid function and generate an output i_r^i . The first tanh function 144a may generate an output. The output i_r^i of the first input gate 134a and the output of the first tanh function 144a may be passed to the element-wise product function 142a. The element-wise product function 142a may generate an output by calculating the element-wise product of the output i_r^i of the first input gate 134a and the output of the first tanh function 144a. The output of the element-wise product function 142a may be element-wise summed 146a with the output of the element-wise product function 128a. The output of the element-wise sum function 146a may be the first partial shared cell state c_r^i 302a. The first partial shared cell state c_r^i 302a may be passed to the first tanh function 154a. The first output gate 152a may include or employ the sigmoid function and generate an output. The output of the first output gate 152a and the output of the first tanh function 154a may be passed to the element-wise product function 156a, which may generate the first partial shared hidden state h_r^i 304a.

The second architecture 300b may include the first gate, which may include the element-wise sum function 212b summing the second sensor encoding s_r^j 104 with the same first shared hidden state h_{r-1} 124 (e.g., provided to the first architecture 300a) and generating the output which may be passed to the second forget gate 126b, the second input gate 134b, the second tanh function 144b, and the second output gate 152b of the second architecture 300b. The second forget gate 126b may include or employ the sigmoid function and generate an output f_r^j . The element-wise product 128b of the output f_r^j of the second forget gate 126b and the same first shared cell state c_{r-1} 122 (e.g., provided to the first architecture 300a) may be calculated.

The second input gate 134b may include or employ the sigmoid function and generate an output i_r^j . The second tanh function 144b may generate an output. The output i_r^j of the second input gate 134b and the output of the second tanh function 144b may be passed to the element-wise product function 142b. The element-wise product function 142b may generate an output by calculating the element-wise product of the output i_r^j of the second input gate 134b and the output

13

of the second tanh function **144b**. The output of the element-wise product function **142b** may be element-wise summed **146b** with the output of the element-wise product function **128b**. The output of the element-wise sum function **146b** may be the second partial shared cell state c_t^i **302b**. The second partial shared cell state c_t^i **302b** may be passed to the second tanh function **154b**. The second output gate **152b** may include or employ the sigmoid function and generate an output. The output of the second output gate **152b** and the output of the second tanh function **154b** may be passed to the element-wise product function **156b**, which may generate the second partial shared hidden state h_t^j **304b**.

As previously noted, the second architecture **300b** may be identical to the first architecture **300a**, except that the second architecture **300b** may receive the second sensor encoding s_t^j **104** as the input rather than the first sensor encoding s_t^i **102**. Element-wise sum functions for the cell state gate **312** and the hidden state gate **314** may sum the first partial shared cell state c_t^i **304a** with the second partial shared cell state c_t^j **304b** and the first partial shared hidden state h_t^i **302a** with the second partial shared hidden state h_t^j **302b**, to generate the second shared cell state c_t **162** and the second shared hidden state h_t **164**, respectively.

The fusion cell of FIG. 5B may be identical or similar to the fusion cell **410**

of FIG. 4, except that the output gate **450** is removed, thereby enabling the first product **552** of the first element-wise product gate **442** and the second product **554** of the second element-wise product gate **444** to be passed to the element-wise sum function **212b** of the second architecture **300b** and the element-wise sum function **212a** of the first architecture **300a**, respectively.

For example, the fusion cell of FIG. 5B may include the first rectifier **412**, the second rectifier **414**, the fusion gate **420**, the sigmoid function gate **430**, the function gate **432**, the first element-wise product gate **442**, and the second element-wise product gate **444**. The first rectifier **412** may receive the first sensor encoding s_t^i from the first sensor and may generate a first adjusted sensor encoding e_t^i . The second rectifier **414** may receive the second sensor encoding s_t^j from the second sensor and may generate a second adjusted sensor encoding e_t^j . The first adjusted sensor encoding e_t^i may be passed to the fusion gate **420** and the first element-wise product gate **442**. The second adjusted sensor encoding e_t^j may be passed to the fusion gate **420** and the second element-wise product gate **444**. The fusion gate **420** may receive the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j and generate a fusion gate result p_t^k , which may be passed to the sigmoid function gate **430**. The output of the sigmoid function gate **430** may be passed to the first element-wise product gate **442** and the function gate **432**. The function gate **432** may calculate a $(1-p_t^k)$ value.

The first element-wise product gate **442** may receive the fusion gate result p_t^k and the first adjusted sensor encoding e_t^i and generate the first product **552**, which may be passed as the input to the element-wise sum function **212b** of the second architecture **300b**. The second element-wise product gate **444** may receive the $(1-p_t^k)$ from the function gate **432** and the second adjusted sensor encoding e_t^j and generate the second product **554**, which may be passed as the input to the element-wise sum function **212a** of the first architecture **300a**. In this way, the first product **552** may be an input to a first gate (e.g., the element-wise sum function **212b**) of the second architecture **300b** within the LSTM cell employing an element-wise sum function summing the first product **552** and the hidden state h_{t-1} . Similarly, the second product **554**

14

may be input to a first gate (e.g., the element-wise sum function **212a**) of the first architecture **300a** within the LSTM cell employing an element-wise sum function summing the second product **554** and the hidden state h_{t-1} .

$$e_t^i = \text{relu}(W_e^i * s_t^i), \quad (7)$$

$$p_t^k = \sigma \left(\sum_{i=1}^M W_p^i * e_t^i \right), \forall k \in [1, m-1] \quad (8)$$

$$a_t = \left(\sum_{k=1}^{M-1} p_t^k \odot e_t^k \right) + \left(1 - \sum_{k=1}^{M-1} p_t^k \right) \odot e_t^M, \quad (9)$$

$$f_t = \sigma(W_f * a_t + U_f * H_{t-1} + b_f),$$

$$i_t = \sigma(W_i * a_t + U_i * H_{t-1} + b_i),$$

$$o_t = \sigma(W_o * a_t + U_o * h_{t-1} + b_o),$$

$$g_t = \tanh(W_g * a_t + U_g * h_{t-1} + b_g), \quad (10)$$

$$c_t = c_{t-1} \odot f_t + i_t \odot g_t,$$

$$h_t = o_t \odot \tanh(c_t), \quad (11)$$

$$e_t^j = \text{relu}(W_e^j * s_t^j) \quad (12)$$

$$p_t^k = \sigma \left(\sum_{i=1}^M W_p^i * e_t^i \right), \forall k \in [1, M-1], \quad (13)$$

$$a_t^i = \begin{cases} p_t^i \odot e_t^i & \text{if } i \in [1, M-1], \\ \left(1 - \sum_{k=1}^{M-1} p_t^k \right) \odot e_t^M & \text{if } i = M \end{cases}$$

$$f_t^i = \sigma(W_f^i * a_t^i + U_f^i * h_{t-1} + b_f^i),$$

$$i_t^i = \sigma(W_i^i * a_t^i + U_i^i * h_{t-1} + b_i^i),$$

$$o_t^i = \sigma(W_o^i * a_t^i + U_o^i * h_{t-1} + b_o^i),$$

$$g_t^i = \tanh(W_g^i * a_t^i + U_g^i * h_{t-1} + b_g^i), \quad (14)$$

$$c_t^i = c_{t-1} \odot f_t^i + i_t^i \odot g_t^i,$$

$$h_t^i = o_t^i \odot \tanh(c_t^i), \quad (15)$$

$$c_t = \sum_{i=1}^M c_t^i, h_t = \sum_{i=1}^M h_t^i \quad (16)$$

FIG. 6 is an exemplary component diagram of a system **600** for sensor fusion associated with the LSTM cells of FIGS. 1-5, according to one aspect. The system for sensor fusion may include a processor **602**, a memory **604**, a storage drive **606**, a communication interface **608**, an LSTM module **612**, a gated fusion module **614**, and a bus **642**. The LSTM module **612** and/or the gated fusion module **614** may be implemented via the processor **602** and execute or perform one or more of the functions described above with reference to FIGS. 1-5, such as performing the element-wise sum function, the element-wise product function, the tanh function, the sigmoid function, etc. The system **600** for sensor fusion may be implemented within a vehicle and be associated with one or more vehicle systems. In this regard, driver behavior classification and/or driver behavior prediction may be performed based on the inputs received, such as the first sensor encoding s_t^i and the second sensor encoding s_t^j from the first sensor **102** and the second sensor **104**, respectively. As discussed, any number (M number) of sensors or modalities may be considered although merely two sensors (i.e., associated with the first sensor encoding s_t^i and the second sensor encoding s_t^j) are discussed herein.

15

FIG. 7 is an exemplary flow diagram of a method 700 for sensor fusion associated with the LSTM cells of FIGS. 1-5, according to one aspect. The method 700 may include receiving 702 a first sensor data within the LSTM cell, receiving 704 a second sensor data data within LSTM cell separate from the first sensor data, processing 706 the first sensor data using a first forget gate within the LSTM cell, processing 708 the second sensor data using a second forget gate within the LSTM cell different than the first forget gate, processing 710 the first sensor data using a first input gate within the LSTM cell, processing 712 the second sensor data using a second input gate within the LSTM cell different than the first input gate, generating 714 a first output using a first output gate within the LSTM cell and a cell state, and generating 716 a second output using a second output gate within the LSTM cell and the cell state.

FIG. 8 is an exemplary flow diagram of a method for sensor fusion associated with the LSTM cells of FIGS. 1-5, according to one aspect. The method 800 may include receiving 802 M number of sets of sensor data within the LSTM cell from M number of sensors, processing 804 M number of sets of sensor data using M number of forget gates within LSTM cell corresponding to the M number of sets of sensor data, processing 806 M sets of sensor data using M number of input gates within LSTM cell, and generating 808 M number of outputs (to determine an updated cell state and updated hidden state) using M number of output gates within LSTM cell and the previous cell state.

FIG. 9 is an exemplary flow diagram of a method 900 for sensor fusion associated with the LSTM cells of FIGS. 1-5, according to one aspect. The method 900 for sensor fusion may include generating 902 a first adjusted sensor encoding based on a first sensor encoding from a first sensor, generating 904 a second adjusted sensor encoding based on a second sensor encoding from a second sensor, generating 906 a fusion result based on the first adjusted sensor encoding and the second adjusted sensor encoding, generating 908 a first product based on the fusion result and the first adjusted sensor encoding, generating 910 a second product based on the second adjusted sensor encoding, receiving 912 either the first sensor encoding or the first product and the first shared hidden state at a first forget gate of an LSTM cell, receiving 914 the second sensor encoding or the second product and the first shared hidden state at a second forget gate of the LSTM cell, receiving 916 the first sensor encoding or the first product and the first shared hidden state at a first input gate of the LSTM cell, receiving 918 the second sensor encoding or the second product and the first shared hidden state at a second input gate of the LSTM cell, generating 920 a first output based on the first shared cell state, the first sensor encoding or the first product, and the first shared hidden state at the first output gate, generating 922 a second output based on the first shared cell state, the second sensor encoding or the second product), and the first hidden state at the second output gate, generating 924 a second shared hidden state based on the first output and the second output at a hidden state gate, and generating 926 a second shared cell state based on an output of first forget gate, an output of second forget gate, an output of first input gate, and an output of second input gate at a cell state gate.

Still another aspect involves a computer-readable medium including processor-executable instructions configured to implement one aspect of the techniques presented herein. An aspect of a computer-readable medium or a computer-readable device devised in these ways is illustrated in FIG. 10, wherein an implementation 1000 includes a computer-readable medium 1008, such as a CD-R, DVD-R, flash

16

drive, a platter of a hard disk drive, etc., on which is encoded computer-readable data 1006. This encoded computer-readable data 1006, such as binary data including a plurality of zero's and one's as shown in 1006, in turn includes a set of processor-executable computer instructions 1004 configured to operate according to one or more of the principles set forth herein. In this implementation 1000, the processor-executable computer instructions 1004 may be configured to perform a method 1002, such as the method 700 of FIG. 7, the method 800 of FIG. 8, or the method 900 of FIG. 9. In another aspect, the processor-executable computer instructions 1004 may be configured to implement a system, such as the system 600 of FIG. 6. Many such computer-readable media may be devised by those of ordinary skill in the art that are configured to operate in accordance with the techniques presented herein.

As used in this application, the terms "component", "module," "system", "interface", and the like are generally intended to refer to a computer-related entity, either hardware, a combination of hardware and software, software, or software in execution. For example, a component may be, but is not limited to being, a process running on a processor, a processing unit, an object, an executable, a thread of execution, a program, or a computer. By way of illustration, both an application running on a controller and the controller may be a component. One or more components residing within a process or thread of execution and a component may be localized on one computer or distributed between two or more computers.

Further, the claimed subject matter is implemented as a method, apparatus, or article of manufacture using standard programming or engineering techniques to produce software, firmware, hardware, or any combination thereof to control a computer to implement the disclosed subject matter. The term "article of manufacture" as used herein is intended to encompass a computer program accessible from any computer-readable device, carrier, or media. Of course, many modifications may be made to this configuration without departing from the scope or spirit of the claimed subject matter.

FIG. 11 and the following discussion provide a description of a suitable computing environment to implement aspects of one or more of the provisions set forth herein. The operating environment of FIG. 11 is merely one example of a suitable operating environment and is not intended to suggest any limitation as to the scope of use or functionality of the operating environment. Example computing devices include, but are not limited to, personal computers, server computers, hand-held or laptop devices, mobile devices, such as mobile phones, Personal Digital Assistants (PDAs), media players, and the like, multiprocessor systems, consumer electronics, mini computers, mainframe computers, distributed computing environments that include any of the above systems or devices, etc.

Generally, aspects are described in the general context of "computer readable instructions" being executed by one or more computing devices. Computer readable instructions may be distributed via computer readable media as will be discussed below. Computer readable instructions may be implemented as program modules, such as functions, objects, Application Programming Interfaces (APIs), data structures, and the like, that perform one or more tasks or implement one or more abstract data types. Typically, the functionality of the computer readable instructions are combined or distributed as desired in various environments.

FIG. 11 illustrates a system 1100 including a computing device 1112 configured to implement one aspect provided

herein. In one configuration, the computing device **1112** includes at least one processing unit **1116** and memory **1118**. Depending on the exact configuration and type of computing device, memory **1118** may be volatile, such as RAM, non-volatile, such as ROM, flash memory, etc., or a combination of the two. This configuration is illustrated in FIG. **11** by dashed line **1114**.

In other aspects, the computing device **1112** includes additional features or functionality. For example, the computing device **1112** may include additional storage such as removable storage or non-removable storage, including, but not limited to, magnetic storage, optical storage, etc. Such additional storage is illustrated in FIG. **11** by storage **1120**. In one aspect, computer readable instructions to implement one aspect provided herein are in storage **1120**. Storage **1120** may store other computer readable instructions to implement an operating system, an application program, etc. Computer readable instructions may be loaded in memory **1118** for execution by processing unit **1116**, for example.

The term “computer readable media” as used herein includes computer storage media. Computer storage media includes volatile and nonvolatile, removable and non-removable media implemented in any method or technology for storage of information such as computer readable instructions or other data. Memory **1118**

and storage **1120** are examples of computer storage media. Computer storage media includes, but is not limited to, RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, Digital Versatile Disks (DVDs) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which may be used to store the desired information and which may be accessed by the computing device **1112**. Any such computer storage media is part of the computing device **1112**.

The term “computer readable media” includes communication media. Communication media typically embodies computer readable instructions or other data in a “modulated data signal” such as a carrier wave or other transport mechanism and includes any information delivery media. The term “modulated data signal” includes a signal that has one or more of its characteristics set or changed in such a manner as to encode information in the signal.

The computing device **1112** includes input device(s) **1124** such as keyboard, mouse, pen, voice input device, touch input device, infrared cameras, video input devices, or any other input device. Output device(s) **1122** such as one or more displays, speakers, printers, or any other output device may be included with the computing device **1112**. Input device(s) **1124** and output device(s) **1122** may be connected to the computing device **1112** via a wired connection, wireless connection, or any combination thereof. In one aspect, an input device or an output device from another computing device may be used as input device(s) **1124** or output device(s) **1122** for the computing device **1112**. The computing device **1112** may include communication connection(s) **1126** to facilitate communications with one or more other devices **1130**, such as through network **1128**, for example.

Although the subject matter has been described in language specific to structural features or methodological acts, it is to be understood that the subject matter of the appended claims is not necessarily limited to the specific features or acts described above. Rather, the specific features and acts described above are disclosed as example aspects.

Various operations of aspects are provided herein. The order in which one or more or all of the operations are

described should not be construed as to imply that these operations are necessarily order dependent. Alternative ordering will be appreciated based on this description. Further, not all operations may necessarily be present in each aspect provided herein.

As used in this application, “or” is intended to mean an inclusive “or” rather than an exclusive “or”. Further, an inclusive “or” may include any combination thereof (e.g., A, B, or any combination thereof). In addition, “a” and “an” as used in this application are generally construed to mean “one or more” unless specified otherwise or clear from context to be directed to a singular form. Additionally, at least one of A and B and/or the like generally means A or B or both A and B. Further, to the extent that “includes”, “having”, “has”, “with”, or variants thereof are used in either the detailed description or the claims, such terms are intended to be inclusive in a manner similar to the term “comprising”.

Further, unless specified otherwise, “first”, “second”, or the like are not intended to imply a temporal aspect, a spatial aspect, an ordering, etc. Rather, such terms are merely used as identifiers, names, etc. for features, elements, items, etc. For example, a first channel and a second channel generally correspond to channel A and channel B or two different or two identical channels or the same channel. Additionally, “comprising”, “comprises”, “including”, “includes”, or the like generally means comprising or including, but not limited to.

It will be appreciated that various of the above-disclosed and other features and functions, or alternatives or varieties thereof, may be desirably combined into many other different systems or applications. Also that various presently unforeseen or unanticipated alternatives, modifications, variations or improvements therein may be subsequently made by those skilled in the art which are also intended to be encompassed by the following claims.

The invention claimed is:

1. A fusion cell associated with a long short-term memory (LSTM) cell, comprising:

- a first rectifier receiving a first sensor encoding s_t^i from a first sensor and generating a first adjusted sensor encoding e_t^i ;
- a second rectifier receiving a second sensor encoding s_t^j from a second sensor and generating a second adjusted sensor encoding e_t^j ;
- a fusion gate receiving the first adjusted sensor encoding s_t^i and the second adjusted sensor encoding e_t^j and generating a fusion gate result p_t^k ;
- a first element-wise product gate receiving the fusion gate result p_t^k and the first adjusted sensor encoding e_t^i and generating a first product;
- a second element-wise product gate receiving $(1-p_t^k)$ and the second adjusted sensor encoding e_t^j and generating a second product; and
- an output gate receiving the first product and the second product and generating a fused state a_t .

2. The fusion cell of claim **1**, wherein the first rectifier or the second rectifier is a rectified linear unit (ReLU).

3. The fusion cell of claim **1**, wherein the fusion gate employs an element-wise sum function and a sigmoid function to generate the fusion gate result p_t^k based on the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j .

4. The fusion cell of claim **1**, wherein the first element-wise product gate or the second element-wise product gate employ an element-wise product function to generate the first product or the second product, respectively.

5. The fusion cell of claim 1, wherein the output gate employs an element-wise sum function to generate the fused state a , based on the first product and the second product.

6. The fusion cell of claim 1, wherein the first adjusted sensor encoding $e_t^i = \text{relu}(W_e^{i*} s_t^i)$.

7. The fusion cell of claim 1, wherein the fusion gate result $p_t^k = \sigma(\sum_{i=1}^M W_p^{i*} e_t^i)$, $\forall k \in [1, m-1]$.

8. The fusion cell of claim 1, wherein the fused state $a_t = (\sum_{k=1}^{M-1} p_t^k \odot e_t^k) + (1 - \sum_{k=1}^{M-1} p_t^k) \odot e_t^M$.

9. The fusion cell of claim 1, wherein the fused state a_t is input to a first gate of the LSTM cell employing an element-wise sum function summing the fused state a_t and a hidden state h_{t-1} .

10. The fusion cell of claim 9, wherein an output of the first gate of the LSTM cell is passed as an input to a forget gate of the LSTM cell.

11. A fusion cell associated with a long short-term memory (LSTM) cell, comprising:

a first rectifier receiving a first sensor encoding s_t^i from a first sensor and generating a first adjusted sensor encoding e_t^i ;

a second rectifier receiving a second sensor encoding s_t^j from a second sensor and generating a second adjusted sensor encoding e_t^j ;

a fusion gate receiving the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j and generating a fusion gate result p_t^k ;

a first element-wise product gate receiving the fusion gate result p_t^k and the first adjusted sensor encoding e_t^i and generating a first product; and

a second element-wise product gate receiving $(1 - p_t^k)$ and the second adjusted sensor encoding e_t^j and generating a second product.

12. The fusion cell of claim 11, wherein the first adjusted sensor encoding $e_t^i = \text{relu}(W_e^{i*} s_t^i)$.

13. The fusion cell of claim 11, wherein the fusion gate result $p_t^k = \sigma(\sum_{i=1}^M W_p^{i*} e_t^i)$, $\forall k \in [1, m-1]$.

14. The fusion cell of claim 11, wherein the fusion gate employs an element-wise sum function and a sigmoid function to generate the fusion gate result p_t^k based on the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j .

15. The fusion cell of claim 11, wherein the first product is input to a first gate of a first architecture within the LSTM cell employing an element-wise sum function summing the first product and a hidden state h_{t-1} .

16. The fusion cell of claim 11, wherein the second product is input to a first gate of a second architecture within the LSTM cell employing an element-wise sum function summing the second product and a hidden state h_{t-1} .

17. A method for sensor fusion associated with a long short-term memory (LSTM) cell, comprising:

generating a first adjusted sensor encoding e_t^i based on a first sensor encoding s_t^i from a first sensor;

generating a second adjusted sensor encoding e_t^j based on a second sensor encoding s_t^j from a second sensor;

generating a fusion result p_t^k based on the first adjusted sensor encoding e_t^i and the second adjusted sensor encoding e_t^j ;

generating a first product based on the fusion result p_t^k and the first adjusted sensor encoding e_t^i ;

generating a second product based on $(1 - p_t^k)$ and the second adjusted sensor encoding e_t^j ; and

generating a fused state a , based on the first product and the second product,

wherein the fused state a_t is input into a first gate.

18. The method for sensor fusion of claim 17, wherein the first adjusted sensor encoding $e_t^i = \text{relu}(W_e^{i*} s_t^i)$.

19. The method for sensor fusion of claim 17, wherein the fusion result $p_t^k = \sigma(\sum_{i=1}^M W_p^{i*} e_t^i)$, $\forall k \in [1, m-1]$.

20. The method for sensor fusion of claim 17, wherein the fused state $a_t = (\sum_{k=1}^{M-1} p_t^k \odot e_t^k) + (1 - \sum_{k=1}^{M-1} p_t^k) \odot e_t^M$.

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